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Understanding the effects of sand and dust accumulation on photovoltaic modules

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Abstract

Numerical and analytical models of sand and dust particle accumulation on photovoltaic modules in dry regions are presented and supported by a laboratory investigation of sand particle accumulation on a glass surface. Both models and the experimental data indicate that the reduction in the free fractional area can be described by an exponential decay resulting from the formation of clusters of particles. Such clusters can support particles in upper layers which reduce the available area for photon capture by a much smaller amount than particles resting directly on the glass surface. The results qualitatively describe existing field data beyond the linear regime and are developed to account for field conditions, including analysis of photovoltaic module tilt, humidity and wind speed. This investigation is intended as a basis of an engineering design tool to assess the case for including photovoltaics in dry regions.

Keywords: sand, dust, accumulation, photovoltaic, cluster

1. Introduction

The accumulation of sand and dust on the surface of photovoltaic (PV) modules has been shown in both field studies [1, 2] and laboratory experiments [3–5], to have a negative impact on their performance. These particles block incident photons from reaching the PV cells and consequently reduce the output electrical power from the module. This is a particular problem for dry regions (defined as Group B in the Köppen climate classification scheme [6]) such as the Middle East and North Africa where wind-driven sand and dust particles are a characteristic of the local environment. These regions are favourable locations for PV installations as a result of high average irradiance levels and the availability of land. Furthermore, economic development in countries such as the United Arab Emirates, Saudi Arabia and Qatar has driven the construction of many new buildings which offer the potential for building integrated photovoltaics (BIPV). Sustainability in these projects is increasingly important as engineering companies' clients demand internationally recognised green building accreditation.

Although the accumulation of wind-driven sand ($\sim 60 - 2000\,\mu$m diameter) and dust (silt $\sim 4 - 60\,\mu$m and clay $< 4\,\mu$m diameter [7]) particles on PV modules has been shown to reduce the output electrical power, these results have not translated to an engineering tool that can be used by PV designers and engineers to assess the environmental and business cases for the inclusion of PV in a building project in these locations.

Al-Hasan developed a model for the reduction in PV module efficiency caused by the accumulation of sand and dust particles [8]. This was based on a particle reducing the PV collection area by its cross-sectional area. This model was successfully employed to describe the reduction in PV output up to $\sim 50\%$ for a field experiment in Kuwait. Beyond this however the model failed to account for a non-linear effect observed in the experimental data. In a separate field experiment in Egypt, Elminir *et al*. observed reductions in PV output power of up to 80% [2]. These authors offered an empirical expression for the reduction in light transmittance as a function of dust deposition density however the physical origins of this empirical model were not presented and it has not been used to describe other experimental findings.

In this work we present a first principles approach to understanding sand and dust accumulation on PV modules in dry regions. Our objective is to create the foundations of an engineering tool which can be used to assess the potential effect on PV performance for a given amount of accumulated sand particles. We demonstrate how the results from a laboratory experiment designed to simulate sand and dust accumulation on PV modules can be described over a wide range by an essentially exponential decay and explain the underlying physical processes. Our analysis is supported by numerical simulations and data from existing published work.

2. Material and methods

Simulation of sand accumulation on PV modules was performed in a laboratory environment under controlled conditions. Although this is not an accurate representation of field conditions, it permits investigation of the fundamental processes leading to a reduction in the incident sunlight levels.

SiO_2 particles from the company Sigma Aldrich Ltd. (Dorset, UK) were deposited on a glass slide of dimensions

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$76 \times 26 \times 1$ mm and mass 4.70804 ± 0.00005 g by a manual sieving process. This involved adding particles to a liquid strainer of diameter 60 mm and average mesh size of 0.48 ± 0.03 mm. For finer separation, a linen fabric of average mesh size along the short and long length of the weave of 0.29 ± 0.05 mm and 0.6 ± 0.1 mm respectively, was placed inside the metal strainer. The average radius of deposited particles was measured to be 170 ± 20 μm. All length measurements were calibrated by first imaging a ruler at the same microscope magnification. Particles were deposited over the whole slide which was located in a stable horizontal position above a computer controlled Veho VMS-004D optical microscope. This arrangement enabled acquisition of digital images for analysis and also allowed observation of sand accumulation in real-time. After the desired sand coverage had been achieved and images such as those shown in figure 1 recorded, the slide was weighed using a Sartorius MC-210S precision balance. This instrument was located immediately next to the microscope and care was taken not to disturb the particles during this step. Particles were then cleaned from the slide before it was returned to its initial position above the microscope in preparation for a subsequent deposition of particles.

A variation on this process was used to investigate the effect of the height from which the particles were deposited on the obtained coverage. This involved depositing the particles over a defined area on the glass which was the same size as the microscope aperture and aligned with a fixed sieve position. Following a deposition, images were acquired before excess particles located outside the defined area were carefully removed and the slide was weighed. Analysis of the particle coverage in both deposition methods produced the same results confirming the independence of the deposition method on the resulting coverage.

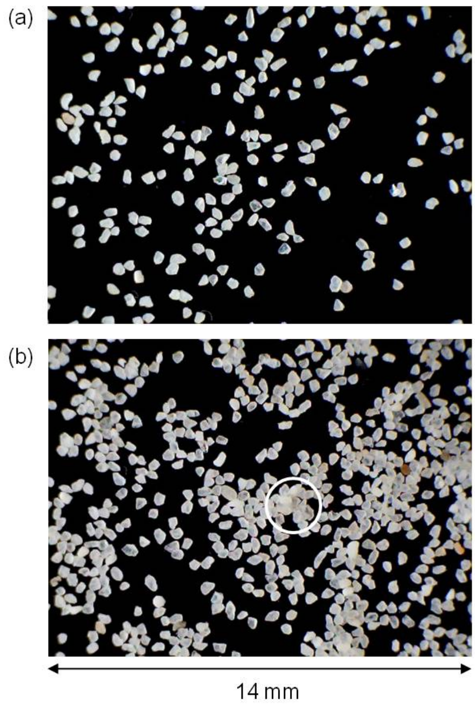

Figure 1: Accumulation of sand particles on a glass substrate. The circled area in (b) is an example of clustering in which particles in the first layer are able to support further particles in the upper layer.

3. Results

3.1. Experimental investigation

Images of particle accumulation on the glass slide were obtained for different amounts of sand. Figure 1 shows digital images acquired for two different quantities of particles deposited on the surface. The masses of the deposited particles were (a) 0.04005 ± 0.00005 g and (b) 0.20051 ± 0.00005 g. Nearly all the particles in figure 1a rest directly on the glass. In figure 1b however, particle clustering is observed as a result of the increased quantity of sand on the glass. It is evident that these clusters can support further particles thereby creating upper layers of particles which are not in direct contact with the glass.

A grain threshold algorithm in the software package Gwyddion, was used to determine the free fractional area A, of the glass i.e. that which is not covered by particles. Since this is a two-dimensional analysis, A is in fact a vertically projected area. Figure 2 shows that this quantity decreases exponentially with increasing amounts of sand. The introduction of a gentle disturbance (created by lightly tapping the edge of the glass slide) causes the sand to settle and A is observed to decrease more rapidly with mass of sand. This rearrangement effect becomes more pronounced with increasing sand accumulation as

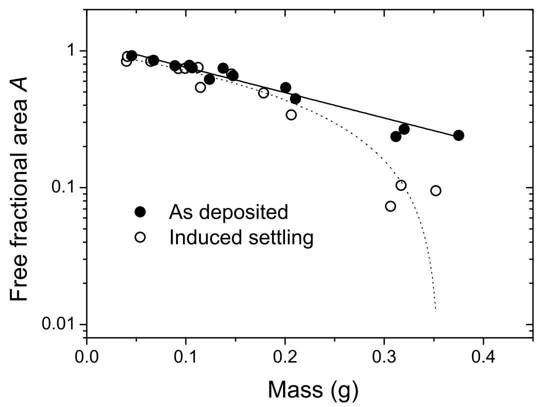

Figure 2: Reduction in the free fractional area of a glass slide with increasing quantities of sand. Filled circles show the as-deposited coverage while open circles show coverage after application of gentle disturbance to the glass slide. The solid and dotted lines are exponential and linear fits to the data respectively.

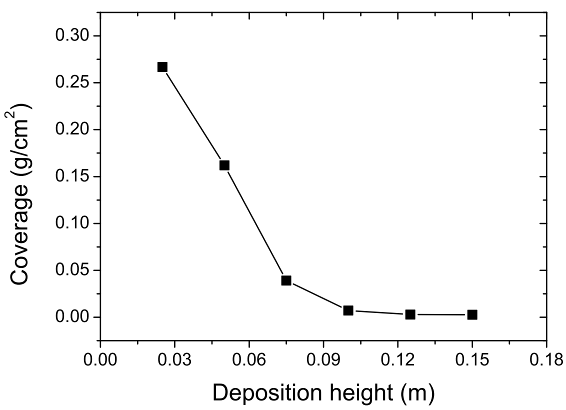

Figure 3: Experimental data showing particle coverage as a function of deposition height. For each deposition, the mass of particles deposited was kept constant.

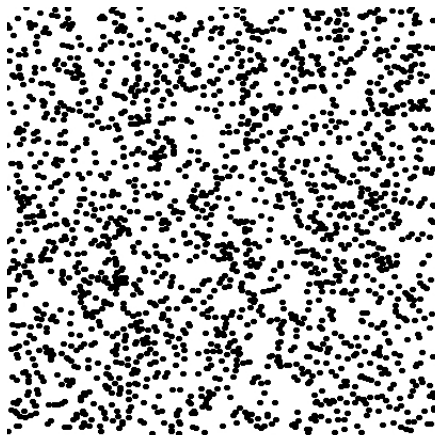

Figure 4: A Monte Carlo approach was used to simulate particle accumulation on PV modules. The figure shows an example image obtained for $n = 2000$ particles. Images were obtained for other values of n and subsequently analysed.

a result of clustering and the formation of upper layers of particles.

Figure 3 shows how the density of particles on the surface of the glass varies as a function of the height from which they were deposited. Deposited particles were observed to bounce upon impact with the glass surface. As the height of deposition was increased, the density of particles on the surface reduced since some particles bounced off the glass slide. This observation clearly depends upon the size of the glass slide and is addressed in section 4.3.

3.2. Model of sand and dust accumulation

We now qualitatively explain the dependence of the free fractional area on mass shown in figure 2. The addition of a sand particle to the the first layer reduces the available area of the glass slide by approximately the sand particle's cross sectional area and the decrease in A is linear. Initially, all sand particles are distant from each other and subsequent particles landing on them cannot be supported and fall onto the glass. In this regime, the free fractional area decreases linearly with sand mass. As more particles arrive on the surface, clusters are gradually formed and there is an increasing probability that subsequent particles will land on a cluster rather than on the glass. This causes the evolution of the free area to deviate from the linear behaviour described in previous work [8]. The relaxation of particles into a lower energy state following a gentle disturbance destroys the clusters and recovers the linear behaviour in free fractional area as shown in figure 2. We will first present a simple model that captures the origin of the exponential behaviour and then show how it can be extended.

The origin of the exponential behaviour of the as-deposited data in figure 2 can be captured analytically by considering the addition of particles of an arbitrary shape to the slide. The total area of the particles deposited as a fraction of the total area of the slide is N. As each particle carries a fixed area, N is proportional to the mass per unit area of particles on the slide. Although mass density is an experimentally convenient unit, N is a more natural measure as it directly reflects the exposed particles ability to reduce light transmission. However, the free fractional area A is not simply $1 - N$ because particles overlap. This behaviour can be captured mathematically by noting that, for small particles, the probability of a particle landing on free glass area is $1 - A$ such that

$$\frac{dA}{dN} = 1 - A \Rightarrow A = 1 - e^{-N}. \quad (1)$$

Another approach to modelling the accumulation of sand and dust particles on PV modules is to use a Monte Carlo method. For this purpose, we created a program using National Instruments LabVIEW that randomly distributes circular dots within a square area. The program was used to generate a series of images each having a different number n, of distributed dots and an example of which is shown in figure 4. Analysis of the obtained images was performed using the same method as described in section 3.1 and it can be seen in figure 6 that the results are in complete agreement with the simple analytical model.

While this simple model conveniently provides insight, there are important differences between it and reality. In particular, it is clear that there is a limit to how closely grains can pack together and that some, but not all grains can support a second grain. To capture this behaviour we introduce the two dimensional random close packing fraction $\alpha \sim 0.8$ [9], and the fractional filling level F_i of a given layer i, such that the most a layer of filling F_i can contribute to obscuring the surface is αF_i. We introduce the cluster function $c(F_i)$ describing the fraction of sand grains that sit within a cluster. For illustration, we have evaluated the cluster function using a square lattice and the condition that a filled site must, with its neighbours, be part of a triangle to determine that it is part of a supporting cluster. The algorithm and resulting functions are shown in figure 5. It should be noted that this is intended to approximate the experimental system, capturing its behaviour qualitatively rather than precisely. Differences arise in the continuous nature of sand positions and the fact that in practice, sand particles bounce before

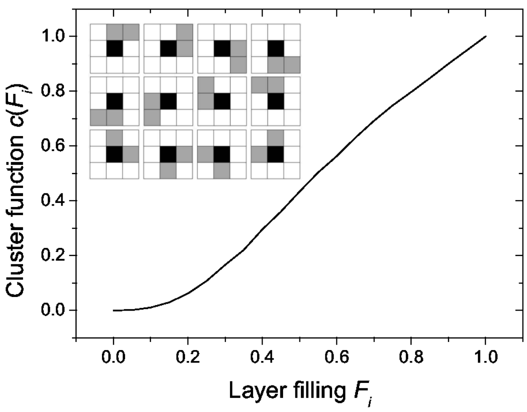

Figure 5: Fraction of particles within a square lattice that form part of nearest neighbour triangles and are thus able to support an upper layer of particles. Inset shows all possible geometric combinations.

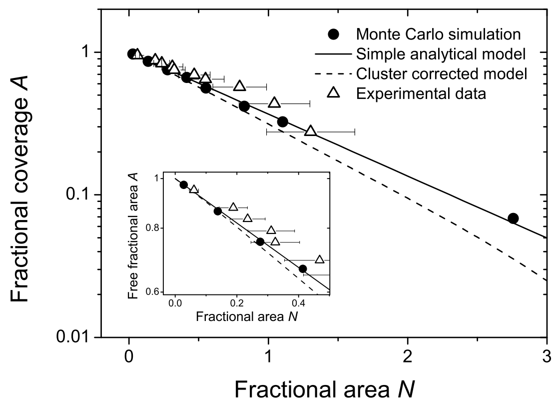

Figure 6: The free fractional area of the slide A versus the fractional area N for an analytical model (equation 1), a numerical model and a cluster corrected analytical model (equation 3) that more closely resembles the accumulation of sand particles on PV modules. Also shown are results of an experiment in which sand particles were deposited upon a glass slide under laboratory conditions. The inset is a magnification of the data at low coverage.

coming to rest, potentially disrupting clusters, and delaying the onset of cluster formation.

Recalling that the close packing fraction α must be used to connect the fractional area N and filling fractions F_1 and F_2, the evolution of the layers is described by:

$$\alpha \frac{dF_1}{dN} = 1 - c(F_1) \qquad \alpha \frac{dF_2}{dN} = c(F_1)[1 - c(F_2)], \tag{2}$$

while the total exposed area is given by

$$A = 1 - \alpha F_1 - (1 - \alpha) F_2, \tag{3}$$

and is shown in figure 6. We note that the behaviour is again exponential over several orders of magnitude but decays more quickly than equation 1 as only a subset of particles are able to support an upper layer.

4. Discussion

4.1. Comparison of theory and experiment

Previous studies of sand and dust accumulation on PV modules assess the particle coverage in terms of mass or mass per unit area. While this is also the case in our experiment, we can perform a comparison with our models by expressing the coverage in terms of N. The deposition of a small number of non-overlapping particles allowed calculation of the average weight of one particle. For each point in figure 2 it was then possible to determine the number of particles deposited and their total area. This in turn, allowed us to calculate experimental values of N which are shown figure 6. The agreement between our experiments and models is good and broadly within experimental uncertainty.

4.2. Influence of particle size

In a previous study it was observed that smaller particles cause a greater reduction in the short circuit current of a PV module than larger particles when the coverage was measured in g/m^2 [3]. This was attributed to the uniformity of the distribution of particles however, this needs to be interpreted with care: for equivalent mass per unit area, a larger area of the PV module is obscured by the distribution of smaller particles therefore reducing the electrical output of the PV module. Our approach to the problem is advantageous in that the analysis is reduced to a ratio of two areas and indeed when performing the Monte Carlo simulation with different sizes of dots, the results are identical. In our investigation we have kept the particle size constant in both the experiment and the modelling for simplicity and to gain fundamental insight, however differences will arise for smaller particles such as dust. We anticipate that for particles of mixed size distributions smaller particles are able to fill the voids between big particles and further reduce the available PV area for photon capture.

4.3. Accumulation threshold

As shown in figure 3, the accumulation of particles depends non-linearly on the height from which the particles are deposited. This is a result of particles bouncing off the slide. For bounce angles

$$\theta_m > \frac{1}{2} \sin^{-1}\left(\frac{xg}{v^2}\right), \tag{4}$$

where x is the distance to the edge of the slide and v is the particle's velocity, particles will bounce off the slide. The fraction of solid angles within this limit is therefore $1 - \cos\theta_m$ where $\cos\theta_m$ is the fraction of particles that do not accumulate. Noting that $v = v_0 C_R$ where C_R is the coefficient of restitution and $v_0^2 = 2gh$ then we can re-write equation 4 in terms of h i.e. the height of deposition. Neglecting the effect of rectangular slide geometry for simplicity, and evaluating this expression for $x \sim 0.05$ m and $C_R \sim 0.5$ we find $h \sim 0.1$ m which is in good agreement with the accumulation threshold identified in figure 3. We note that the accumulation threshold occurs at approximately twice the length of the slide, i.e. for heights greater than $x/2C_R^2$. This insight could have potential implications for PV module spacing within an array if detailed information about the local sand transport is available. The situation for dust particles will be different as the process of accumulation will be less elastic and clusters will be more stable as a result of increased cohesion between particles.

4.4. Extension to field conditions

Three significant variables that are not included in our models but found in field conditions are module tilt, moisture and wind speed. Before addressing these however, consider Figure 7 which shows the results of a field study by Al-Hasan [1]. In this study, the effect of sand and dust accumulation on the normalised efficiency of PV modules orientated at 30° to the horizontal in Kuwait was determined as a function the areal density of particles. In contrast to the original publication, we have presented this data on semi-logarithmic axes to show the qualitative agreement with our model of exponential decay. We note that this agreement extends beyond the range of the linear model presented by Al-Hasan.

Increasing the PV module tilt angle affects the stability of the clusters up to a critical angle θ_c, whereupon an avalanche process occurs. For perfect spheres in a random packing configuration, this has been theoretically determined to be $\theta_c = 23.4°$ [10]. However, this increases when rolling friction and non-spherical particles are taken into account and in an experiment on sand the angle of repose $\theta_r = 33 \pm 2° < \theta_c$ [11]. The presence of naturally occurring moisture on a PV module's surface will create a cohesive force between particles through surface tension such that θ_c further increases from the dry case in proportion to the ratio of the cohesive force to the particle's weight [10]. It is conceivable that for a tilted module, sand and dust particles will preferentially accumulate towards the bottom of the module where the frame may act as a supporting structure. In this case, the electrical output would be limited by a particular region of accumulation (as is the case for shading) rather than the free fractional area. However, analysis of $(2\gamma r)/(\mu mg)$ where γ is surface tension, r is the particle radius, m is the particle mass and μ is the coefficient of friction ($\sim$ 1 for dry glass), indicates that the force required to overcome surface tension is approximately two orders of magnitude greater than that of friction for our representative particles. We therefore expect that under field conditions, particles on a tilted module will adhere to the glass rather than collect around the module frame.

The combination of these factors leads us to believe that the clustering behaviour we observed in our experiments is also present in the process that resulted in the data shown in figure 7. It is also interesting to note the slight modulation of the data in figure 7 and we speculate that this may be a consequence of the clustering process through the non-linearity of $c(F_i)$. Qualitatively, we expect similar results for other PV installations in dry regions where 30° is a typical PV module tilt angle for optimum electricity generation.

The effect of wind can be accounted for qualitatively by considering that for an isolated particle on an entirely dry and flat

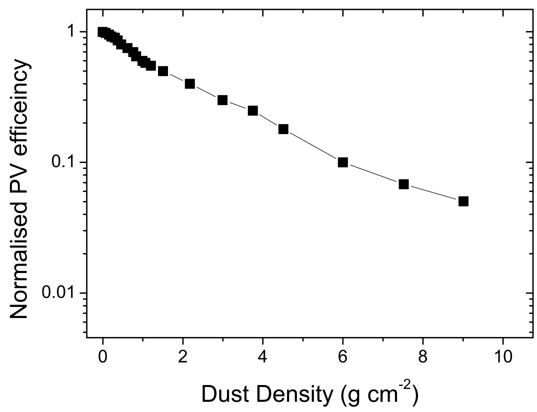

Figure 7: Experimental data from an investigation of the effect of sand and dust accumulation on PV module performance in Kuwait by Al-Hasan [1].

PV module to be removed by the wind, it requires sufficient energy to overcome the frictional force. Assuming a coefficient of friction for glass of $\mu = 1$, a particle mass of $m = 10\ \mu$g and a PV module length of $L = 1$ m, this corresponds to an equivalent wind velocity of $v \simeq 5$ m/s. Such wind speeds are typical and, under completely dry conditions, we therefore expect to a first approximation that as many particles are removed by the wind as deposited. In reality, atmospheric humidity will increase the energy requirement through surface tension in which case, particles will remain on the PV module for wind speeds up to an order of magnitude greater. Furthermore, for smaller particles, adhesion to the module surface will increase as a result of increased cohesion forces between particles. This crude analysis is presented to show that the relationship between moisture on the PV and wind speed is an important one that strongly influences particle accumulation and should be a focus for future experimental investigation.

5. Conclusions

We have presented numerical and analytical models of sand and dust accumulation on PV modules in dry regions which are in quantitative agreement with a laboratory investigation of particle accumulation on a glass slide. The process of accumulation can be described over an order of magnitude by an exponential decay which is the result of particle clustering. We have extended the results to account for variables likely to be encountered in an actual installation and find qualitative agreement with existing data over a greater range than previously achieved. With further quantitative investigation of field conditions, these results are the basis of an engineering tool for building projects that include PV in dry regions. Finally, we note that the results of this work can be generalised to solar thermal and glazing applications.

References

[1] A. Y. Al-Hasan, A. A. Ghoeneim, A new correlation between photovoltaic panel's efficiency and amount of sand dust accumulated on their surface,

Int. J. Sus. Energy 24 (2005) 187–197.

[2] H. K. Eliminir, A. E. Ghitas, R. H. Hamid, F. E. Hussainy, M. M. Beheary, K. M. Abdel-Moneim, Effect of dust on the transparent cover of solar collectors, Energy Convers. Manage. 47 (2006) 3192–3203.

[3] M. S. El-Shobokshy, F. M. Hussein, Effect of dust with different physical properties on the performance of photovoltaic cells, Sol. Energy 51 (1993) 505–511.

[4] D. Goosens, E. V. Kerschaever, Aeolian dust deposition on photovoltaic solar cells: The effects of wind velocity and airborne dust concentration on cell performance, Sol. Energy 66 (1999) 277–289.

[5] H. Jiang, L. Lu, K. Sun, Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules, Atmos. Environ. 45 (2011) 4299–4304.

[6] M. C. Peel, B. L. Finlayson, T. A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (2007) 1633–1644.

[7] A. S. Goudie, N. J. Middleton, Dust Entrainment, Transport and Deposition, Springer, 2006.

[8] A. Y. Al-Hasan, A new correlation for direct beam solar radiation received by photovoltaic panel with sand and dust accumulated on its surface, Sol. Energy 63 (1998) 323–333.

[9] H. Solomon, Random packing density, in: Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, 1967.

[10] R. Abert, I. Albert, D. Hornbaker, P. Schiffer, A. Barabási, Maximum angle of stability in wet and dry spherical granular media, Phys. Rev. E 56 (1997) 6271–6274.

[11] R. L. Brown, J. C. Richards, Principles of Powder Mechanics, Pergamon Press, 1970.